Sulfometuron Methyl: Its Use in Forestry and Potential Phytotoxicity

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Abstract: Planting site preparation is a common practice used to enhance seedling establishment success. Site preparations include herbicide, fire, and mechanical methods. Studies designed to explore the use of herbicides as site preparation and release tools are common, and herbicides have shown their use in forestry to be logistically, economically, and ecologically advantageous. Herbicides that pose little threat to animal health or off-site contamination are desirable for forest management. Sulfometuron and related herbicides have been identified as effective vegetation suppressants with little collateral environmental impact. However, most research involving site preparation with sulfometuron has tested for efficacy and environmental safety alone, without addressing potential herbicide influence on growth of desirable species. Because the growth of seedlings is often a primary concern in forestry herbicide use, growth suppression is undesirable. Some research recognizing the potential for sulfometuron to damage tree seedlings has been conducted, but most emphasis lies with eastern US hardwoods and southeastern US softwoods that show species-specific tolerance levels. Little study has been conducted to explore the effects of sulfometuron on important species of the northwestern US, despite its use there. The few experiments conducted in the west have focused only on a few species. Widespread and important species such as western white pine (*Pinus monticola*), western larch (*Larix occidentalis*), and interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) have received little or no study with sulfometuron, despite their value and current use in intensively-managed forests; ideally the information presented in this paper will serve as a basis for new research to fill this information gap. The deficit of knowledge concerning potential detrimental effects of sulfometuron on these species calls for further research to establish best-use practices for individual species and site factors.

Keywords: sulfometuron, phytotoxic, seedling, site preparation, nursery

Introduction

Actions taken to prepare a forest planting site can aid in seedling establishment and success. These practices are aimed at reducing risk to planted or natural regeneration and promoting rapid forest establishment, growth, and productivity by reducing competition for resources.

Today, herbicides are frequently more appropriate than mechanical methods or fire for intensive-management forestry site preparation and release treatments. While unintentional ecological impact is a risk, herbicides have the advantage of relatively low cost, low soil disturbance, functionality in areas with difficult access, and improved control of re-sprouting species (Otchere-Boateng and Herring 1990).

Given the variable effects of individual species and herbicide combinations, there is great value in focusing study on one particular site-preparation herbicide (Seifert and Woeste 2002). The herbicide sulfometuron-methyl (methyl 2-[[[[(4,6-dimethyl-2-pyrimidinyl) amino]-carbonyl]amino]sulfonyl]benzoate), known by the trade names, Oust® and Oust® XP (hereafter referred to as sulfometuron), is a member of an increasingly popular family of herbicides available for forestry use (Russell and others 2002). Sulfometuron is used to chemically control herbaceous competition in the establishment and maintenance of forest plantations in the southeastern, eastern, and northwestern US (Anderson and Dulka 1985). Studies correlating sulfometuron to tree seedling damage and mortality, however, are rare, and this area invites further analysis.

Sulfonylurea Herbicides

Sulfonylureas are generally broad-spectrum herbicides first commercialized in 1981 (DuPont 2002). They function by inhibiting the plant growth enzyme acetolactate synthase (ALS) (Obrigawitch and others 1998). ALS participates in the biosynthesis of the branched-chain amino acids valine, leucine, and isoleucine, which are essential to normal, healthy cell division and growth (Blair and Martin 1988). Root meristem tissues are especially affected by disruption of the ALS enzyme function (Brown 1990). These root meristem cells eventually senesce and, without any viable growing points, the entire plant succumbs (Russell and others 2002).

Because all plants use the ALS enzyme for cell division and maturation, sulfonylureas rank low for plant species/group selectivity (Russell and others 2002). As with other sulfonylureas, ALS inhibition is the essential mode of action for sulfometuron, and while growth inhibition is fast (less than 3 hours in typical applications), target plant death is slow, often exceeding 4 weeks (Blair and Martin 1988). Sulfometuron is even less selective than most sulfonylureas (Russell and others 2002), and this fact means it can be used effectively as both a pre- and post-emergent herbicide (DuPont 2007).

Apart from their ability to target most weed species, sulfonylureas have several desirable characteristics separating them from other herbicide families. Due to the high specific activity of the ALS inhibitor, sulfonylureas such as sulfometuron can be used at very low application rates. Rates for field applications are generally over 100 times lower than those for older, conventional herbicides (Obrigawitch and others 1998). These low application rates translate to decreased chemical volumes and logistic expense, and the feasibility of effectively and economically treating large land areas. Besides low application rates, sulfonylureas have the advantage of a long application window, that is, whenever target plants are actively growing (Russell and others 2002) However, the advantage gained by this long application window is offset by the nonselective nature of the herbicide. Sulfometuron selectivity can often only be obtained by applying the herbicide when crop species are made less susceptible by dormancy and strong establishment (Cox 2002).

Environmental Fate

While sulfometuron has minimal impact on human health and aquatic fauna (Michael 2003; Michael and others 2006), it does persist in, and to a small extent travel through, the spray site environment. Its persistence in the environment is dependent upon a number of site-specific factors (Green and Strek 2001; Russell and others 2002). Once sulfometuron has been applied to a site, it will follow one of several fates. Ideally, it will be taken up into target plant tissues where it will be translocated to root and shoot meristems. It could also potentially be degraded on exposed surfaces, end up in surface water channels, or be adsorbed into the soil surface. As a class, sulfonylureas are essentially non-volatile (Russell and others 2002).

If sulfometuron molecules are unable to penetrate plant surfaces and be taken up into tissues, photolysis (degradation via ultraviolet sunlight) is probable. DuPont (2007) reports that most exposed Oust® not taken up by target vegetation is chemically destroyed by sunlight. Several other research efforts have confirmed this claim (Harvey and others 1985; EXTOXNET 1994; Green and Strek 2001; Michael and others 2006). The photolysis half-life for sulfometuron is reportedly 1 to 3 days (Harvey and others 1985). Photolyzed sulfometuron poses little further threat to the ecosystem because resulting compounds are herbicidally inert and ecologically harmless (Russell and others 2002). If sulfometuron is not photolytically destroyed, it may diffuse or percolate into surface runoff. Michael (2003) and Michael and others (2006) reported that off-site movement of sulfometuron occurred only after significant storm flow events and at no time were aquatic sulfometuron concentrations high enough to be detrimental to local aquatic invertebrates. The outcomes of these studies and others indicate that while most sulfometuron remains within the treatment site, it is capable of moving into aquatic systems and could thereby be moved off-site, although little or no damage is done to those systems because most residues are quickly photolytically or hydrolytically degraded.

Sulfometuron in the Soil

Apart from those portions which are taken into plant tissues or lost to photolysis, the majority of sulfometuron on treated sites is integrated into the soil. For pre-emergent herbicide activity, soil integration is desirable. Any herbicide not taken up by underground plant tissues is eventually degraded hydrolytically or metabolically. Because it does have potential for lasting soil activity, however, much study has been done to assess the fate of sulfometuron incorporated into treated soil.

Once in the soil, sulfonylureas degrade through both abiotic and biotic processes (Russell and others 2002). Soil microbe populations metabolize sulfometuron into its inert components. While this metabolizing action removes the chemical from the soil at a continuing rate, the speed of this process is dependent on factors affecting soil microbial activity and populations (Michael and others 2006). No study has yet been done to determine the percentage of herbicide degraded metabolically, but it can be inferred that, depending on application rate, a significant amount of residue is broken down in this fashion, especially in basic soils. The remainder is degraded through abiotic processes.

As in aqueous systems, abiotic breakdown of sulfometuron in the soil is the primarily result of chemical hydrolysis (Michael and Neary 1993). The speed of this process is directly influenced by the chemical and material composition of the soil, as well as moisture content and temperature. Drier soils prolong residue presence, as do high soil pH and low temperature values (Russell and others 2002; Michael and others 2006). As a family, sulfonylureas are weakly acidic, and that results in some chemical properties, such as solubility and susceptibility to hydrolysis, being pH dependent. The rate of sulfometuron soil hydrolysis is described as being slowest under conditions of neutral or alkaline pH, while acidic conditions are particularly effective in promoting degradation by destabilizing chemical bonds (Russell and others 2002). Harvey and others (1985) analyzed the hydrolysis of the active ingredient under various pH conditions and found that at pH 5.0, the half-life of sulfometuron was approximately 14 days. Conversely, measurements taken 30 days after treatment for pH 7.0 and 9.0 in another study showed 87% and 91% of the active chemical remaining, respectively (Anderson and Dulka 1985). Because of this apparently wide-ranging variation in the longevity of active residue in the soil due to pH-dependent hydrolysis, implications for treating neutral or alkaline forest soils are great. While pH is reportedly the most influential factor in determining sulfometuron persistence, other soil properties, such as composition, also affect hydrolysis and movement (Russell and others 2002). Soils with a high percentage of organic material tend to adsorb sulfometuron at a greater rate than mineral or sandy soils. It has also been suggested that soil pH values below the pH (5.2) of the herbicide greatly increase its hydrophobicity, contributing to its affinity for soil carbon molecules (Oliveira and others 2001). Once bound into a soil carbon complex, sulfometuron is essentially inert and will be degraded via one of the pathways already described.

Temperature is also influential in determining the rate of sulfometuron degradation. Although no studies have correlated soil temperature to residue persistence, DuPont (2007) suggests that lower temperatures slow the degradation process. This is primarily due to decreased biotic and hydrolytic activity. A combination of all biotic, climatic, and soil factors determine the rate at which sulfometuron degrades and the duration of the chemical in the soil.

Because of the high specific activity, sulfometuron is one of the longest persisting sulfonylurea herbicides. While figures for residue soil half-life vary, most authors suggest values between 10 to 35 days depending on soil, vegetation, and climate conditions (Harvey and others 1985; EXTOXNET 1994; Trubey and others 1998; Cox 2002; DuPont 2007). In their area-specific review of sulfometuron soil persistence, however, Anderson and Dulka (1985) report that the chemical was detectable in soils up to 12 months after application in eastern US states; in west coast states, conditions allowed persistence up to 18 months; and in the Rocky Mountain states, up to 2 years.

As with most sulfonylureas, sulfometuron has little potential to move off-site and cause serious ecological damage. However, due to its solubility at pH values common in forest soils and its ability to persist for considerable periods under differing soil and climate conditions, sulfometuron has the potential to remain on site and active, continuing to influence the growth of local flora for a wide range of time. This ability to remain active in the soil, coupled with its other weed control characteristics, has made it a common instrument in the practice and research of forest site preparation and management.

Research that strictly concerns the value of sulfometuron for various sites and forest associations is very rare; work comparing it to other herbicides or site treatments is more abundant. Most work, however, focus almost entirely on species native to eastern US forests, especially southeastern plantation species such as loblolly pine (*Pinus taeda*). In a study by Blazier and Clason (2006), two plots initially treated with sulfometuron showed high stand volume and mortality levels, despite the fact that other factors (namely unequal stand densities among plots) affected growth and survival. The researchers suggested the lasting results of herbicide treatment and the initial mortality of weaker individuals accounted for long-term growth advantages by increasing available site moisture and nutrition. In these studies, sulfometuron reportedly performed well and with lasting results.

Studies involving loblolly pine imply or agree that the species is particularly resistant to sulfonylureas (Yeiser and others 2004; Blazier and Clason 2006). Unfortunately, the case is not always true for other eastern species, especially some valuable hardwoods. A study by Ezell (2002) compared the effectiveness of 12 forestry herbicide mixtures, several of which contained sulfometuron. Pre-planting vegetation control was the desired result, so grass and broadleaf herbaceous species, as well as native woody species including loblolly pine, were treated with herbicide mixtures. Overall control with sulfometuron was reported to be very good, especially with respect to longevity. Because of its ability to remain on site and active in the soil, plots treated with sulfometuron regularly exhibited suppression up to 12 months after treatment. When contrasting species survival rates, loblolly pine had higher survival rates than all hardwoods in sulfometuron-treated plots. In one treatment, loblolly pine increased substantially, whereas several oaks (*Quercus* spp.) were completely eliminated by sulfometuron mixtures.

Seifert and Woest (2002) compared four herbicides (one being sulfometuron) and their effects on the growth of outplanted seedlings of nine species of eastern hardwoods and eastern white pine (*Pinus strobus*). Reportedly, seedling performance varied significantly according to species and herbicide mixture. No single treatment ranked above others for all species tested, and while most seedlings showed growth benefits from herbicidal control of competing vegetation, seedlings of a given species grew better under some treatments than others. They found that at least one of the herbicides/combinations resulted in less volume than the control for seven of the ten species examined, indicating that some treatments may have suppressed aboveground growth of tree seedlings as well as weeds. For eastern white pine, sulfometuron resulted in less seedling volume than other herbicides, despite providing better vegetation suppression. Although vegetation control with sulfometuron may be useful in forest site preparation and release, species-specific crop injury is a factor to be considered, especially with some eastern hardwood species.

Rose and Ketchum (2003) addressed the influence of weed control on coastal Douglas-fir growing in the northwest US using Oust®. More recently, Roberts and others (2005) reported on the effects of harvest residue and competing vegetation on soil characteristics and coastal Douglas-fir seedling growth. Again, Oust® was used as a site-preparation and release herbicide for the purpose of establishing weed-control plots as part of a larger experiment. The results of both studies reiterated the value of controlling competing vegetation for the purpose of making growth resources available to crop seedlings, but did not specifically target the effects of sulfometuron as an objective.

Studies investigating the use and effects of sulfometuron in the east contribute valuable information to species-specific sulfometuron susceptibility, as well as the value of sulfometuron, sulfonylureas, and herbicides in general in forest site preparation, plantation establishment, and maintenance. However, transferring the implications of those studies to western forest practices has limited value, and research correlating sulfometuron and western forests is insufficient. In addition these research efforts provide little information about direct interaction between sulfometuron and important timber species. Apart from coastal Douglas-fir, little or no work has been done with other important western timber species, despite the current use of sulfometuron in their management and culture.

Phytotoxicity in Western US Forest Species

The idea that eastern hardwood species are more susceptible to herbicide injury than more tolerant conifers (Seifert and Woeste 2002) has resulted in the use of site treatment herbicides in plantings of relatively un-studied western conifers. A review by Obrigawitch and others (1998) provided information across the spectrum of sulfonylureas and potential non-target species, but very few studies focus directly on phytotoxicity to western timber species. One of the most recent and significant of these was conducted by Burney and Jacobs (2009) who analyzed sulfometuron phytotoxicity in their study of field-planted coastal Douglas-fir, western hemlock (Tsuga heterophylla), and western redcedar (Thuja plicata). While root growth reductions in treated seedlings were seen the first year after planting, they had recovered to control levels after the second year. However, the authors suggest that soil and climate conditions on their study sites were conducive to residue breakdown; that given the reductions in root growth, seedling survival and establishment may be compromised in a commercial scale situation; and that growth setback may eliminate any vegetation control benefits.

Cole and Newton (1989) reported on height growth and weed suppression in Christmas tree plantations. Sulfometuron at several rates ranging from 0.05 to 0.21 kg ai/ha (0.04 to 0.19 lb/ac) was applied to Douglas-fir, grand fir (*Abies grandis*) and noble fir (*Abies procera*) pre- and post-bud break. Vegetation suppression was reportedly equally effective for sulfometuron and two other herbicides being tested (atrazine and hexazinone), but levels of injury differed significantly between herbicide, treatment rates, and application timing. Indications of injury included needle chlorosis, height growth reduction, and diminished overall appearance. Noble fir showed no significant foliar damage from any treatment, although the highest rate of sulfometuron did slow growth significantly. Similarly, grand fir was apparently uninjured by all treatments and rates. One-year Douglas-fir, however, showed significant injury under all treatment regimes, as evidenced by needle chlorosis and stunting. For older Douglas-fir trees (≥3 years), injury was less apparent, and only cosmetic damage was reported as significant for trees in that age class. Post-bud break treatments in Douglas-fir resulted in more damage than pre-bud break treatments. Overall, sulfometuron treatments resulted in the worst growth of Douglas-fir compared to the other herbicides considered.

In 2002, the Agricultural Products division of DuPont published an addition to the generic Oust® label (DuPont 2002). This special, local-needs label outlined directions and general use information for low spray volume conifer release and site treatment applications in the state of

Washington. This new literature provided general directions for the treatment of important western timber species, but most are lumped together without regard for individual species tolerance levels. According to the label, western timber species, except western redcedar, should be treated with 0.11 to 0.21 kg ai/ha (0.10 to 0.19 lb/ac). This is in spite of the fact that some variations in tolerance between these species have already been established. Lower applications (0.11 to 0.16 kg ai/ha [0.10 to 0.14 lb/ac]) to western redcedar are suggested due to the susceptibility of this species to injury (DuPont 2002). This publication indicates the lack of information on species-specific sulfometuron tolerance levels for western timber species, and is indicative of the degree to which Oust® is being used in western forestry applications.

Nursery Seedling Phytotoxicity Trials

Given the importance of herbicides such as sulfometuron in intensive forest management in the inland northwest of the US, and the inherent tradeoff between control of competing vegetation and phytotoxic damage to crop seedlings (Wagner and others 2007), a more complete understanding of seedling-herbicide interaction is needed to refine use practices and insure timely seedling establishment. In an effort to address this knowledge deficit, two nursery trials using seedlings in large containers were conducted to assess the effects of sulfometuron and two important soil variables controlling residue persistence. These trials were designed to control for all sulfometuron-degrading variables except substrate pH and moisture, and to address these study objectives: 1) determine the effect of substrate pH on herbicide phytotoxicity relative to herbicide application rate; 2) determine the effect of substrate moisture on herbicide phytotoxicity relative to herbicide application rate; and 3) assess the relative sensitivities of three important conifers native to the US inland northwest to different levels of sulfometuron. We hypothesized that higher concentrations of herbicide would result in decreases in measurable growth parameters, and that higher substrate moisture and lower substrate pH would moderate phytotoxicity by hastening residue breakdown.

Experimental Design, Data Collection, and Analysis

This study consisted of two experiments, both conducted at the University of Idaho Center for Forest Nursery and Seedling Research, Pitkin Forest Nursery (Moscow, ID). Both experiments were set up in a completely randomized design to test sulfometuron concentration and one of two soil parameters as causal variables, with growth and physiological responses as dependent variables. Prior to planting, 7.7-L (2-gal) pots (TPOT3; Stuewe and Sons, Incorporated, Tangent, OR) were filled with commercial potting mix, treated with various concentrations of Oust®, and aged for 10 days to allow photolytic elimination of exposed soil-surface residues (Harvey and others 1985). Dormant 1+0 western larch, interior Douglas-fir, and western white pine seedlings, grown in Styroblock™ 415C containers (130 cm^3 [7.9 in^3]; Beaver Plastics, Acheson, Alberta), were used in this study.

The first experiment (Trial #1) was designed to determine the influence of various soil moisture levels on sulfometuron phytotoxicity relative to herbicide concentration under controlled conditions. Six rates of sulfometuron (0.0, 0.026, 0.053, 0.105, 0.158, and 0.210 kg ai/ha [0.0, 0.023, 0.047, 0.094, 0.141, 0.188 lb ai/ac]) were applied to pots filled with medium in April 2008. Seedlings were planted individually in pots in May 2008, and grown under one of three randomly assigned moisture regimes: medium drydown to 25%, 21.5%, or 16% volumetric water content prior to irrigation, with n = 8 seedlings per treatment per species. Seedlings were grown without fertilizer in a greenhouse at the Pitkin Forest Nursery until September 2008. During this time medium moisture conditions were monitored using a Field Scout® TDR 300 soil moisture meter (Spectrum Technologies, Southlake, TX) and hand watered to field capacity when needed.

The second experiment (Trial #2) was similar in design to the first, with medium pH level replacing moisture as a treatment. Three levels of sulfometuron (0.0, 0.079, and 0.158 kg ai/ha [0.0, 0.071, and 0.141 lb ai/ac]) and four pH levels (5.0, 5.5, 6.0, and 6.5) were used, with n = 8 seedlings per species per treatment. Medium pH levels were chosen based on native soil pH values in the inland northwest (McDaniel and Wilson 2007). Medium pH was adjusted prior to treatment and planting and subsequently maintained, using irrigation water adjusted with phosphoric acid (H_3PO_4) and hydrated lime ($Ca(OH)_2$). The pH was set and monitored using an IQ 150 pH meter (Spectrum® Technologies, Southlake, TX). Seedlings were planted in July 2008, grown outside, and hand irrigated when volumetric water content neared 25%. Seedlings were removed for final measurement after 35 growing days (August 2008).

Prior to planting, all seedlings were root-washed and initial measurements of growth variables were taken. Root-washing and root volume measurements were conducted using the water displacement method (Burdett 1979). Initial root-collar diameter (RCD) and height were also measured. Final measurements were taken after the onset of dormancy in October 2008 for Trial #1 seedlings. Final measurements of seedlings in Trial #2 were taken in August 2008. These included RCD, height, root volume after root washing (Burdett 1979), and treatment-caused mortality. Measurements of net photosynthesis, transpiration, and stomatal conductance to water vapor were taken for seedlings in Trial #1 using a portable photosynthesis system (Li-6400, Li-Cor® Biosciences, Lincoln, NE). These leaf function variables were measured in July 2008. Sample needles were harvested and dried, and leaf areas calculated using a leaf area meter (Li-3100, Li-Cor® Biosciences, Lincoln, NE). Leaf area measurements were used to correct leaf function measurements for individual sample leaf areas.

Statistical analyses were performed using SAS® software (SAS Institute Incorporated, Cary, NC). Data normality and homogeneity of variance were assessed and determined to be normal and homogeneous, and no transformations were conducted. Correlations between dependent variables and sulfometuron concentration/media moisture regime, and sulfometuron concentration/media pH were conducted using a two-factor ANOVA for each species in each trial. When the F-test for a given dependant variable was significant at $P \leq 0.05$, Tukey's HSD test was used to separate means. Regression analyses were performed to determine relationships between sulfometuron concentration and significantly affected response variables.

Results

Trial #1

None of the growth parameters measured was significantly affected by medium moisture for any of the three species. Treatment-caused mortality was minimal (< 7% for each species), and mortality differences were not statistically significant for any treatments. Only sulfometuron had a significant influence on seedling growth in Trial #1. Western larch height ($P < 0.0001$), RCD ($P < 0.0001$), and root growth ($P < 0.0001$) were strongly inversely correlated with sulfometuron treatment concentration (Figures 1a, 1b, 1c). Douglas-fir height growth differences ($P = 0.0085$) were detected between seedlings treated with 0.0 or 0.053 kg ai/ha (0.0 and 0.047 lb ai/ac) and seedlings treated with 0.210 kg ai/ha (0.188 lb ai/ac) (Figure 2a). Although not significant, Douglas-fir diameter growth tended to decrease with increased sulfometuron concentration (Figure 2b). The two highest levels of sulfometuron (0.158 and 0.210 kg ai/ha [0.141 and 0.188 lb ai/ac]) were different from control seedlings for root volume change ($P = 0.0002$) (Figure 2c). Mean western white pine seedling height

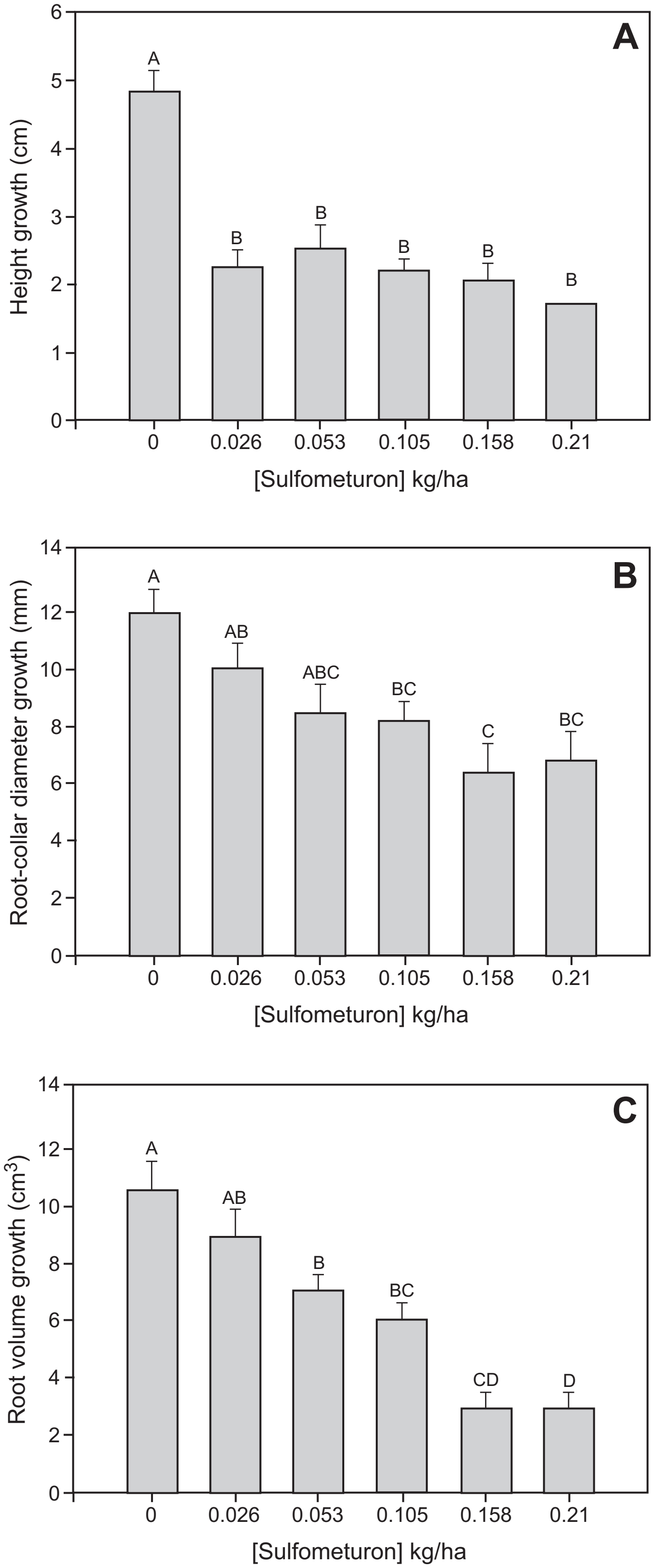

Figure 1. Western larch height growth (A), root-collar diameter growth (B) and root volume growth (C) were inversely correlated with sulfometuron treatment concentration (*P* < 0.0001).

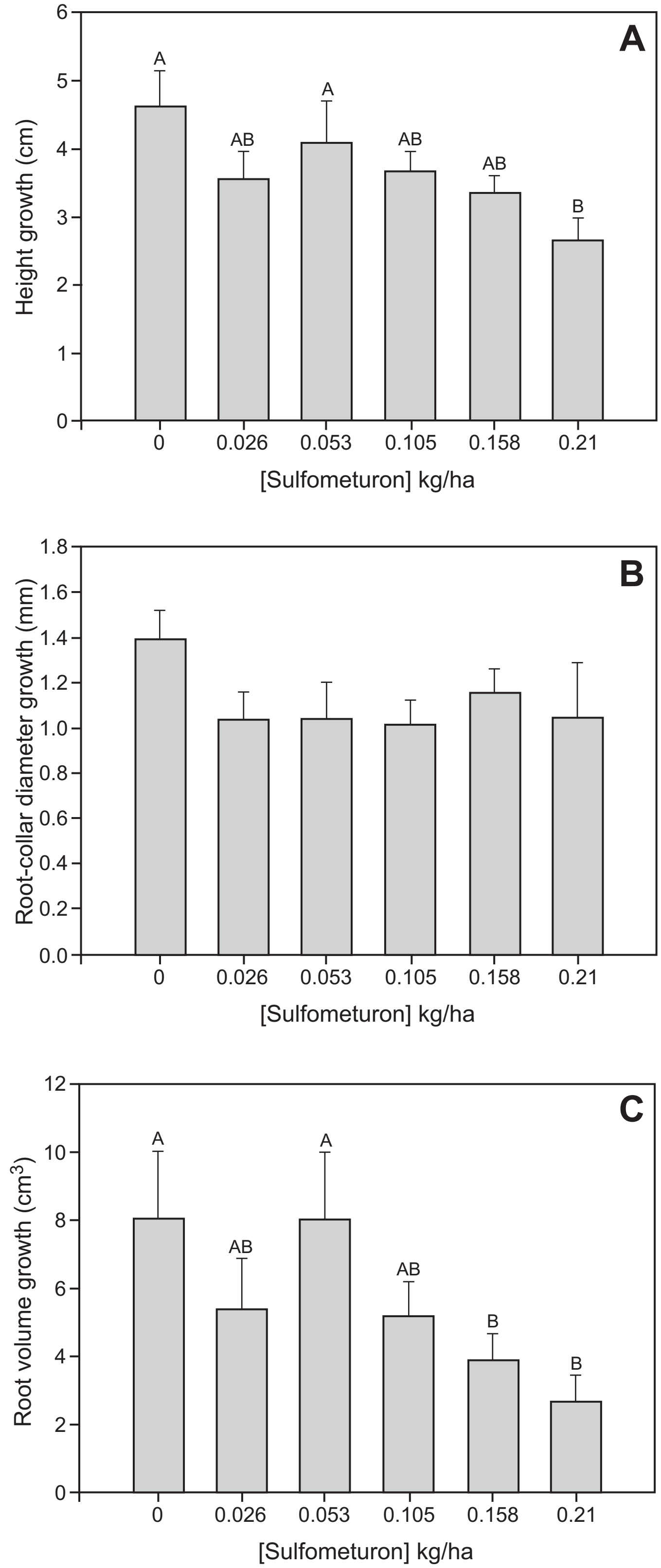

Figure 2. Douglas-fir height growth differences (A) were significant between seedlings treated with 0.0 or 0.053 kg ai/ha (0.0 and 0.047 lb ai/ac) and seedlings treated with 0.210 kg ai/ha (0.188 lb ai/ac). Douglas-fir root-collar diameter growth (B), although not significantly different, tended to decrease with increased sulfometuron concentration. Root volume change in control Douglas-fir seedlings (C) differed from the two highest levels of sulfometuron.

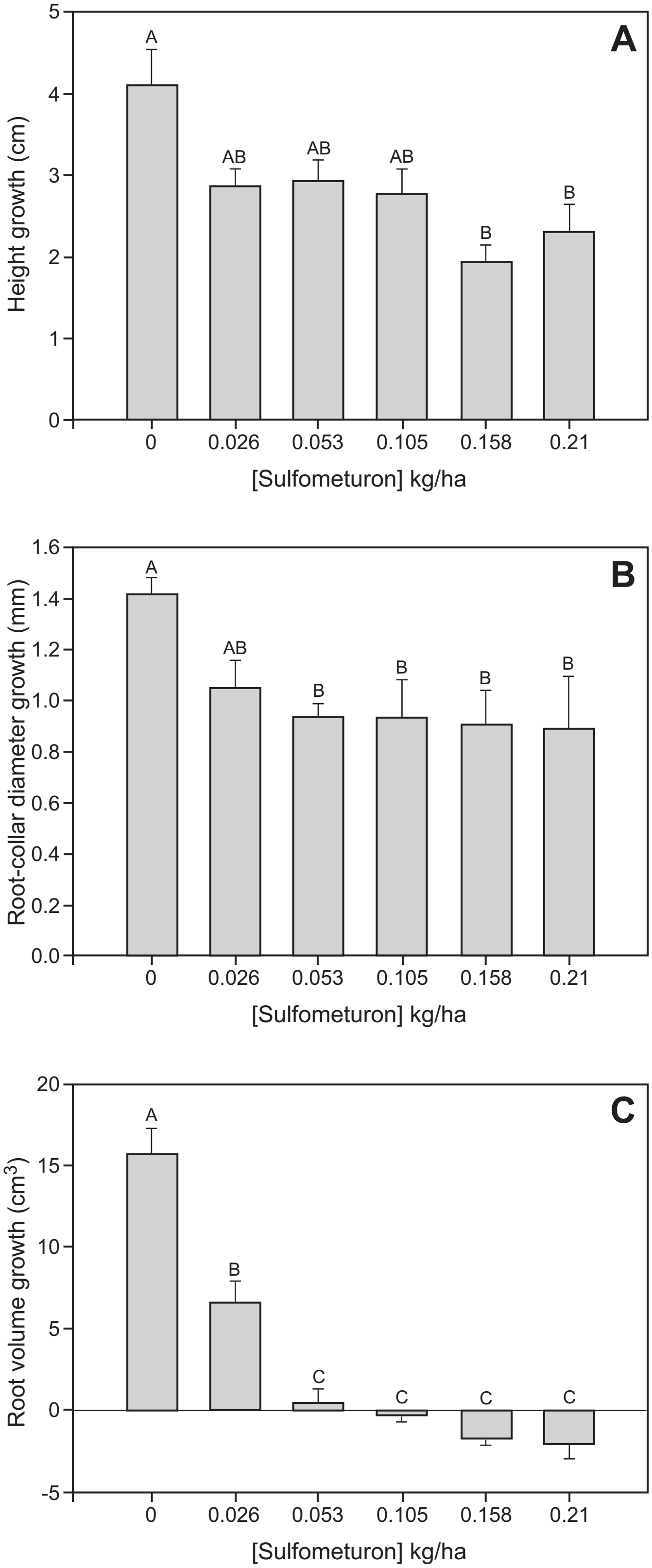

Figure 3. Mean western white pine seedling height growth (A) was significantly less than untreated controls for the two highest levels of sulfometuron only. (B) Western white pine diameter growth (B) differed significantly between controls and the four highest sulfometuron treatment levels. All sulfometuron treatments reduced root volume growth (C) in western white pine.

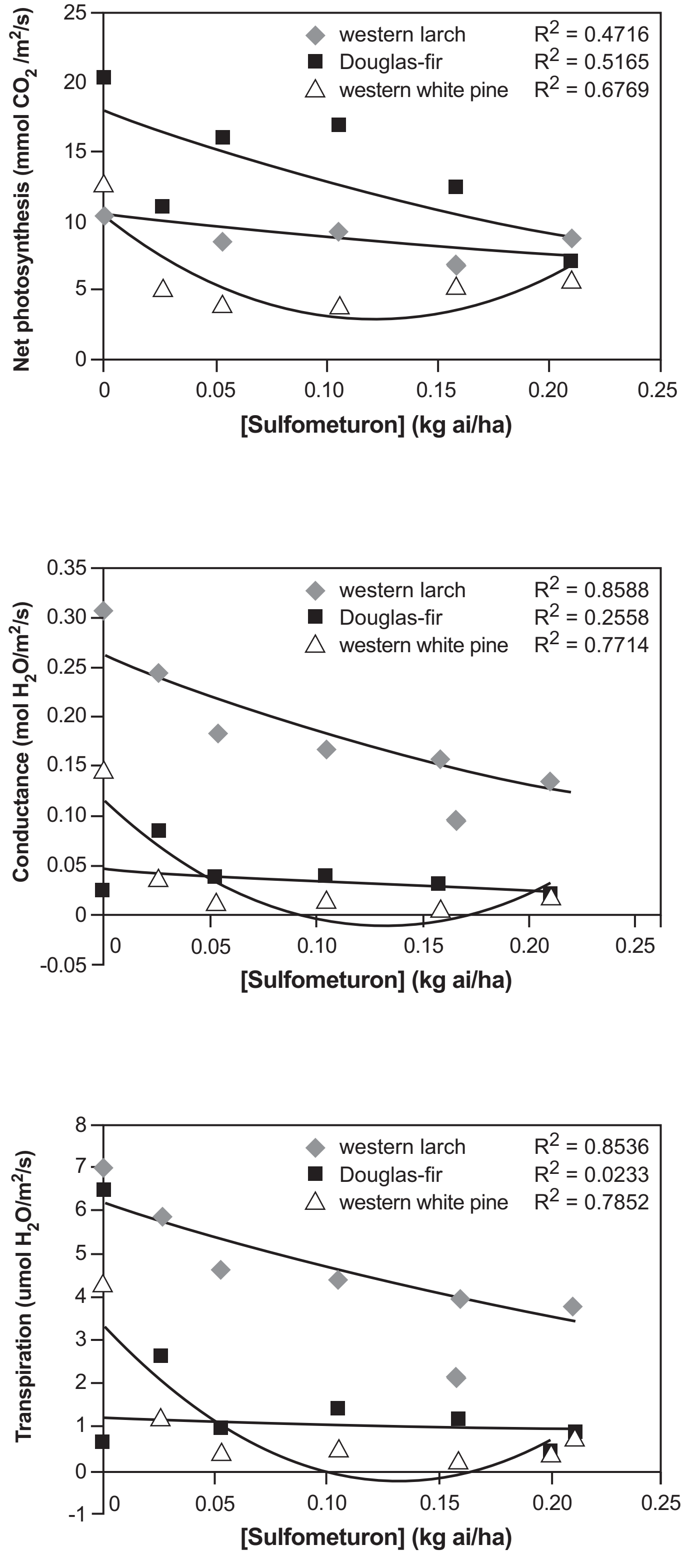

Figure 4. While no significant differences for *A* were apparent for western larch, *gs* and *E* were higher for controls than most herbicide-treated groups. Analyses of Douglas-fir seedlings resulted in no significant differences between treatments. Control western white pine seedlings showed significantly higher *A*, *gs*, and *E* compared to treated seedlings. For *gs* and *E*, all sulfometuron treated groups were significantly lower than the control.

growth was significantly less than untreated controls for the two highest levels of sulfometuron (0.158 and 0.210 kg ai/ha [0.141 and 0.188 lb ai/ac]) only (P = 0.0016) (Figure 3a). For diameter growth, however, the four highest sulfometuron treatment levels differed significantly from controls (P = 0.0008); and for root volume change, all sulfometuron treatments reduced growth (P < 0.0001) (Figures 3b and 3c).

Physiological results were similar to the morphological measurement data. Medium moisture had no effect on the variables of interest: net photosynthesis rate (A), stomatal conductance to water vapor (gs), and transpiration rate (E). Sulfometuron concentration was the only significant treatment variable, and no main-effects interactions were observed. While no significant differences for A were apparent for western larch, gs (P = 0.0002) and E (P = 0.0004) were higher for controls than most herbicide-treated groups (Figure 4). Analyses of Douglas-fir seedlings resulted in no significant differences between treatments. Control western white pine seedlings showed significantly higher A (P = 0.0141), gs (P < 0.0001), and E (P < 0.0001) compared to treated seedlings. For gs and E, all sulfometuron treated groups were significantly lower than the control (Figure 4).

Trial #2

Only sulfometuron concentration was significant in differences in seedling performance for all species. Medium pH did not significantly affect any growth parameter for any species; neither were there any significant main-effects interactions. Treatment-caused mortality was low for all species (< 10%), and not significantly different for any treatments of any species. Larch height growth was significantly affected by sulfometuron (P < 0.0001), with both treated groups differing from the untreated control. Similarly, the influence of herbicide on RCD (P = 0.0148) and root volume (P < 0.0001) was significant. Although only the highest treatment level differed from control means for RCD, root volume was strongly affected, with both treated groups differing from the control. Effects on Douglas-fir seedlings were less apparent, although at least one treatment group differed significantly from the control for height (P = 0.0208), diameter (P = 0.0335), and root volume (P < 0.0001). Control western white pine had significantly more height (P = 0.0378) and RCD (P = 0.0416) growth than seedlings in the highest sulfometuron treatment group. Root volume was again affected (P < 0.0001), and means for both treatment groups differed significantly from the control.

Discussion

Higher medium moisture levels were anticipated to moderate phytotoxic effects of sulfometuron by accelerating hydrolytic residue breakdown (Michael and others 2006). This was not significantly apparent. No effect was seen for any growth variable or for any species tested, and this is indicative of the influence of media moisture and pH relative to sulfometuron application concentration in this trial. Brown (1990) found that soil moisture-dependent sulfonylurea residue breakdown was not strictly a result of hydrolysis, but of a complex interaction of soil moisture, microbial community and activity, temperature, and soil composition. It may be that in non-sterile, native soil, residue breakdown via these intertwined mechanisms reduces sulfometuron phytotoxicity levels beyond what was seen in this trial. These variables were intentionally controlled, however, and any main effects from medium moisture or pH alone were not significant at this timescale.

It should be qualified that for both variables, differences in residue phytotoxicity according to substrate pH and moisture regime may become apparent at longer time periods or under field conditions. The abbreviated nature of this study, which allowed for photolytic degradation of surface residues but restricted the pre-planting period to less than 4 weeks, necessitated exposing seedlings to relatively fresh soil residues. As seen by Burney and Jacobs (2009), site preparation treatments using sulfometuron significantly decreased root growth of seedlings planted several months after treatment. Although seedling recovery was seen in their study, it was partly attributed to favorable breakdown conditions. Compared to the US Inland Northwest, where winters are colder and the climate dryer, the coastal soils and climate in their study may shorten residue persistence timescales by increasing microbial activity and hydrolytic breakdown (Anderson and Dulka 1985). Even so, it is unknown whether such timescales would be compatible with typical commercial operations in the US Pacific Northwest (PNW), much less the US Inland Northwest (INW).

For all response variables addressed in this study, herbicide concentration was the only significant causal variable. Although species were impacted differently, increased levels of herbicide generally coincided with significant decreases in growth and physiological function. In a plantation scenario, restricted conductance and transpiration would jeopardize seedling survival during times of moisture stress, especially in hot, dry summers typical of the INW. Reduced root egress would also increase seedling susceptibility to being removed by ungulate browsing (Burney and Jacobs 2009). Similarly, a restriction in height growth reflects a potential loss of height gain in field situations. Because one purpose of vegetation control is to allow crop seedlings to swiftly overtop competing vegetation, suppression of height growth is counterproductive.

The results of this study suggest that these species vary in degree of vulnerability to phytotoxic damage by sulfometuron. Height growth of untreated western larch controls was 55% greater than sulfometuron treated seedlings. Seedlings in the 0.105 to 0.210 kg ai/ha (0.094 to 0.188 lb ai/ac) label-suggested treatment range showed 40% less diameter growth and 62% less root volume than controls, and reductions in gs and E values of 50% and 43%, respectively. For Douglas-fir, control groups had 31% more height growth, 22% more diameter growth, and 51% more root volume than seedlings in the Oust® treatment groups. Western white pine control groups averaged 43% more height growth and 35% more diameter growth than treated seedlings. Pine root volume in the control groups increased 109% over treated seedlings. As seen in Figure 3a, white pine root volume approached zero net growth near 0.075 kg ai/ha (0.069 lb ai/ac) and atrophy of the existing root mass was evident at concentrations higher than 0.105 kg ai/ha (0.094 lb ai/ac). Leaf function measurements were similar, with untreated seedlings averaging 62%, 87%, and 86% greater A, gs, and E, than treated groups, respectively.

Western larch needle and root length, diameter, and vigor were reduced progressively under increasing treatment levels. If such growth setbacks occur in intensively-managed plantations in the INW, establishment success and efficiency could be compromised. Even in the event of eventual seedling recovery, the positive effects of reduced competing vegetation may be negated for this species (Burney and Jacobs 2009). Douglas-fir may possess a degree of tolerance for sulfometuron, although the results of growth and leaf function measurements were variable for this species. Burney and Jacobs (2009) found coastal Douglas-fir to be the most tolerant of three conifers in their study, and Rose and Ketchum (2003) showed that larger coastal Douglas-fir seedlings tolerated treatment best. Because of the apparent interplay of seedling size and herbicide tolerance, interior Douglas-fir may be the most suitable of the three species in this study for use in conjunction with sulfometuron site preparations. Western white pine seedlings in this study showed a very low degree of tolerance for sulfometuron. We conclude that western white pine is very susceptible to sulfometuron, especially when considering root growth and water transport functions. Seifert and Woeste (2002) saw similar results with eastern white pine, and sulfometuron was ranked last out of 17 herbicides for use with eastern white pine. If such growth constraints are seen in field situations, sulfometuron may jeopardize establishment success even at low treatment levels, and negate any positive effect of reduced competition (Burney and Jacobs 2009).

When considering herbicidal site preparation for all tree species, an application rate threshold exists at which point vegetation control benefits are outweighed by seedling phytotoxicity. With sulfometuron, this threshold may be very low or even impractical for western white pine. Using lower sulfometuron treatment levels than recommended by the label may minimize damage to acceptable levels while still providing a suitable degree of vegetation control for all species, but further trials and field studies should be conducted to establish the efficacy and practicality of these rates.

Conclusion

Contrary to our predictions for objectives 1 and 2 of this study, we conclude that given the conditions of these trials, sulfometuron residue persistence was not so affected by substrate moisture and pH as to show differences in seedling phytotoxic response. In the timetable of these trials, neither variable was significant in overcoming the strong, negative effect of herbicide residue at any application level. Of the three species tested for relative sensitivity to sulfometuron (objective 3), interior Douglas-fir proved fairly resilient, while western white pine, and western larch to a lesser degree, proved sensitive; physiological and growth parameters, especially root growth, were negatively impacted. As a site preparation herbicide, the prospects of sulfometuron efficacy, longevity, ecological safety, and economics are appealing, but in order for its use to be truly profitable, it must be established through further study that the benefits of site preparation with sulfometuron outweigh the potential for seedling damage and growth loss. If it is to be used, seedling size, treatment and outplanting timing, and application rate are among the critical factors to consider in balancing weed control and crop injury, especially in sensitive crop species, and further study should be done to refine use practices.

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